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FeO AND MgO IN PLAGIOCLASE OF LUNAR ANORTHOSITES: IGNEOUS OR METAMORPHIC?
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BACKGROUND: The FeO and MgO contents of plagioclase in lunar anorthosites has been recognized as producing anomalously low FeO and MgO in their equilibrium melts when available partition coefficients are utilized for the appropriate calculations[1,2,3]. Determinations of partition coefficients for FeO from experiments both in Fe crucibles that should maintain low oxygen fugacities[4] and in gas mixing furnaces that provide data on changes of the coefficient with f_{O_2} [3] and also from natural assemblages[5] have been consistent. Use of these coefficients with the FeO contents of plagioclase in lunar anorthosites produces melts with FeO contents that are several times lower than expected. Similarly, both natural and experimentally determined partition coefficients for MgO also produce melts that are several times lower in MgO than expected[3,5], the experimental values producing melts almost twice as low in MgO as the natural values. I have explained these anomalies as resulting from redistribution of FeO and MgO during high-grade thermal metamorphism in the early lunar crust[1]. This process is well demonstrated in terrestrial anorthosites that have undergone upper amphibolite to granulite grades of metamorphism[1] and in meteorites that have been recrystallized[6].

In a recent paper McGee[7] maintains that the FeO and MgO contents of plagioclases in lunar anorthosites retain their original igneous concentrations. He argues that the partition coefficients used to calculate the low FeO and MgO in the melts are inappropriate for two reasons: A.) they will be lower at the higher An contents of lunar plagioclase (An95 to 98) than were produced in the experimental work (An80 to 85) and B.) they will be lower for slowly grown plagioclase as is the case for the plutonic environments that produced lunar anorthosites.

DISCUSSION: In an attempt to resolve argument A.) plagioclases of An90 to 96 have been produced experimentally at the liquidus using previously established procedures[3]. The same starting material from previous work was used, but in order to increase the An content of the plagioclase most of the Na was vaporized under low f_{O_2} and high temperature before commencing the experiments. *The resulting partition coefficients for FeO and MgO in plagioclases of An91 to 96 and melts with 9 to 19% FeO show no significant change from the values at An80 to 85 (Fig 1).* Argument B.) ignores the fact that *plutonic plagioclases contain FeO and MgO at concentrations that are consistent with the partition coefficients of both the experiments and volcanic plagioclases across all An values from 65 to 85*[e.g. 3,5,8]. In fact, the low partition coefficients for FeO that McGee cites from Longhi et al.[4] for plutonic plagioclases are misleading. The only anomalously low partition coefficient for FeO (0.006) from Longhi et al. is from a lunar pink spinel troctolite which has probably undergone a history similar to that of the lunar anorthosites. When partition coefficients for the terrestrial plutonic samples are calculated using the mole % values of [4] they are 0.019, 0.024 and 0.046. However, when converted to weight % values, which is what should have been done for a valid comparison with Phinney's data[1,3], the partition coefficients are 0.024, 0.030 and 0.054, in much closer agreement with the experimental results (~0.03). Furthermore, if one uses the classic Skaergaard study of Wager[9] to select the FeO value in the melt of the LZA section, rather than the olivine-based FeO value of Longhi, the coefficients for Longhi's Skaergaard plagioclases range from 0.029 upward, in excellent agreement with the experimental results. Similar mole% conversions for the MgO partition coefficients produce values of 0.020 to 0.022, in excellent agreement with other values based on natural terrestrial assemblages (0.020-0.023)[5]. Thus, the two arguments that question the validity of the FeO and MgO partition coefficients are found wanting and their application to lunar anorthosites stretches credulity.

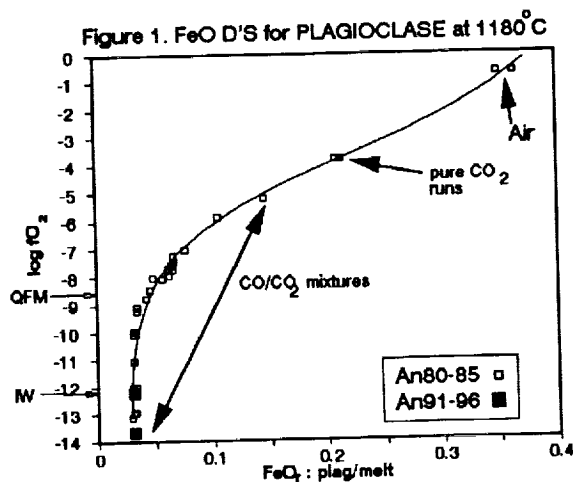
McGee[7] includes a figure from an earlier abstract[10] which shows a regular decreasing trend for FeO and MgO in plagioclase with increasing An content in two mare basalts. The trends are headed directly towards the compositions of plagioclases in lunar anorthosite. At first glance this data would suggest that the partition coefficients do decrease drastically with increasing An content. To take the data at face value, however, would require a change in the partition coefficient for FeO by a nearly impossible factor of ~3 from An86 to An94, given a constant liquid composition. A later extended abstract [11] containing figures with further and more detailed data from this same study indicates that such a simple interpretation is not appropriate. MgO values in the later reference display two oppositely sloped trends over the same range of An values and, in contrast to the earlier figure, the lowest MgO values are actually associated with the lowest An values. Also, FeO values are shown to reverse their trends from early to late-stage plagioclases that display complex textures. In fact, there are both late and early plagioclases at about An90 with 0.5 % FeO which are quite compatible with the experimental partition

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coefficient of 0.030. A plot of mg number vs. An content shows that with progressive crystallization there is a small decrease in mg number with increasing An values during early formation (the reverse of what is expected if olivine and/or pyroxene coprecipitate with plagioclase) and then an even steeper decrease in mg number with decreasing An values during later formation. Clearly substantial changes occurred in the melt composition during the course of plagioclase formation. Complex textural relationships further indicate that: olivine was involved in the early crystallization of one basalt but not in the other, there was precipitation of pyroxenes with plagioclase in both, late-stage precipitation of oxides and quartz occurred in one, and both reversed and normal zoning occurs in the plagioclases. Clearly there were complicated changes in compositions of the melts during the crystallization history of the plagioclases in these two basalts, perhaps even mixing of liquids occurred. *In such complicated textures it is extremely difficult to guess which stage of plagioclase growth was in equilibrium with which composition of liquid. Variation of FeO in the melt by a factor of about 2 from 10-12% to 18-20%, which is certainly possible during crystallization of a basaltic melt, could produce the observed variations.* Thus, given the unknown variation of FeO and MgO concentrations in the melts at the various stages of plagioclase formation, the actual values of partition coefficients are not readily determinable. At this stage of study, the use of these data by McGee in the context of appropriate values for partition coefficients is of questionable utility.

A second point in McGee[7] argues that many lunar anorthosites have not undergone the high temperature metamorphism that would cause redistribution of FeO and MgO. His argument is based on the observation that thin sections of some lunar anorthosites display textural evidence for recrystallization but others do not. To suggest that the textures of a few centimeter-sized chips of lunar anorthosite can be used to determine the recrystallization history of a larger anorthosite unit is to ignore the valuable lessons that are available from large outcrops of terrestrial anorthosites. Terrestrial anorthosites from high grade metamorphic environments may display well preserved igneous textures in numerous enclaves up to a meter across enclosed within totally recrystallized zones[12,13]. *In thin sections coarse-grained igneous textures are maintained immediately adjacent to totally recrystallized textures. Yet, throughout both textures the FeO and MgO contents of the plagioclases are anomalously low*[1]. The low FeO and MgO contents of the plagioclase, whether in clearly recrystallized grains or large, well-twinned, zoned igneous grains, are consistent throughout not only outcrops having dimensions of tens of meters but also metamorphosed units that may extend for kilometers. Thus, the degree of recrystallization observed in centimeter-sized samples does not necessarily reflect the metamorphic context of an entire outcrop and can be quite misleading if used to interpret the petrogenetic history of a rock unit.

SUMMARY: The combined evidence from terrestrial anorthosites and experimental laboratory studies strongly implies that lunar anorthosites have been subjected to high-grade metamorphic events that have erased the igneous signatures of FeO and MgO in their plagioclases. Arguments to the contrary have, to this point, been more hopeful than rigorous.



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